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D6.9 - LONG-TERM ETHICAL AND SOCIAL IMPLICATIONS OF LIQUID ELECTRONICS

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Version and amendments history

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List of Abbreviations

Acronym	
CCS	Colloidal cybernetic systems
EoL	End-of-life
KER	Key Exploitable Result
LCA	Life Cycle Assessment
RRI	Responsible research and innovation
SDG	Sustainable Development Goals

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1 INTRODUCTION

1.1 CONTEXT AND OBJECTIVES OF THE DELIVERABLE

D6.9 – Long-term ethical and social implications of liquid electronics addresses the request of the Ethics Review Panel to provide a forward-looking analysis of the societal and ethical impacts arising from the large-scale development, production, and deployment of liquid electronics.

Within the COgITOR project, liquid electronics are being investigated as a radically new technological paradigm that combines computing, sensing and energy harvesting functionalities within a liquid-based platform. While such advances open promising perspectives in areas such as healthcare, robotics, extreme environment exploration, and sustainable energy, they also raise questions about environmental sustainability, human health and safety, inclusivity, governance frameworks, and public trust.

The main objectives of this deliverable are to:

- **Map ethical dimensions** associated with the development and future scaling of liquid electronics.
- **Identify social implications**, including impacts on employment, equity of access, and societal acceptance.
- **Assess governance challenges** and gaps in current regulatory frameworks that could affect the responsible uptake of these technologies.
- **Collect and integrate stakeholder perspectives** (via survey and COgITOR final workshop consultation) to ensure that the analysis reflects diverse views from academia, industry, policy, civil society, citizens.
- **Provide recommendations** for responsible research and innovation pathways, aligned with European values, international standards, and the UN Sustainable Development Goals.

By addressing these aspects, the deliverable contributes to COgITOR's broader mission of fostering responsible innovation and ensuring that the transition towards liquid electronics is guided by societal needs, ethical principles, and long-term sustainability.

1.2 SCOPE OF ANALYSIS AND METHODOLOGY

The scope of this deliverable extends beyond the laboratory-scale demonstrations of liquid electronics developed within COgITOR, focusing instead on the **long-term societal and ethical implications of their potential large-scale production and deployment**. The analysis adopts a forward-looking perspective, considering not only immediate technical risks but also systemic impacts that could emerge as these technologies transition into industrial, commercial, and societal use.

In particular, the assessment addresses multiple **application domains** where liquid electronics may play a transformative role, such as **healthcare and biomedical devices, consumer wearables, robotics and automation, energy harvesting and storage, and exploration in extreme environments**. Each of these domains raises specific ethical questions: from the safety and regulation of implantable devices to the environmental sustainability of new manufacturing chains, to the social consequences of integrating adaptive and fault-tolerant electronics into critical infrastructures.

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The scope also includes an examination of **cross-cutting societal dynamics**, including the redistribution of employment and skills, equity of access to advanced technologies, the role of public trust and acceptance, and the risk of exacerbating inequalities between regions or social groups. In addition, it considers potential **dual-use and misuse scenarios**, where the same innovations could be repurposed for surveillance, military, or other applications that may conflict with ethical principles.

Timewise, the scope of the analysis is set on a **medium- to long-term horizon (10–20 years)**, recognizing that liquid electronics are still in their early stages of development but may evolve rapidly once industrial pathways are defined. By framing the discussion in this way, the deliverable seeks to anticipate future opportunities and challenges, providing recommendations that can inform research strategies, governance mechanisms, and public dialogue well before widespread adoption takes place.

The methodology adopted in this deliverable combines a **multi-layered desk research** approach with **stakeholder engagement activities**, to provide a comprehensive and balanced view of the long-term ethical and social implications of liquid electronics.

Desk research and literature review

- Analysis of existing ethical frameworks in emerging technologies (responsible R&I, technology assessment, AI ethics, nanotechnology governance).
- Mapping of relevant EU regulatory frameworks, standards, and sustainability policies.
- Review of scientific literature, foresight studies, roadmaps addressing societal and ethical aspects of disruptive technologies.

Stakeholder consultation

- Design and distribution of a targeted **survey** addressing key stakeholder categories (academia and research, SMEs and industry, policymakers and regulators, NGOs and civil society, citizen groups).
- Collection of perspectives from participants in the **Final Workshop (October 2025**) and follow-up exchanges, to enrich the analysis with domain-specific expertise.
- Qualitative analysis of responses to capture both converging and diverging viewpoints.

Analytical framework

The analysis is structured around four main dimensions:

1. **Environmental sustainability**: resource use, recyclability, and end-of-life management.
2. **Human and social aspects**: health and safety, inclusivity, accessibility, equity.
3. **Governance and regulation**: adequacy of current frameworks, dual-use concerns, and needs for certification/standards.
4. **Societal acceptance and foresight**: trust, values, public perception, long-term scenarios

Figure 1. D6.9 methodology.

By combining literature, foresight, and stakeholder insights, the methodology ensures that the deliverable not only identifies potential risks but also highlights opportunities and provides actionable recommendations for responsible innovation pathways.

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1.3 STRUCTURE OF THE DOCUMENT

This deliverable is structured to provide a comprehensive yet focused analysis of the long-term ethical and social implications of liquid electronics. Following the introduction, the document is organised into six main sections.

Section 2 establishes the ethical and social framework, drawing on existing principles, guidelines, and international standards that are relevant for emerging technologies.

Section 3 examines the ethical challenges raised by the large-scale production of liquid electronics, including environmental sustainability, human health and safety, and end-of-life considerations.

Section 4 analyses the broader social implications, such as impacts on employment, societal acceptance, inclusivity, and potential unintended consequences.

Section 5 reviews regulatory and governance aspects, identifying current gaps and outlining the role of standards, certification, and oversight in ensuring responsible uptake.

Section 6 presents stakeholder perspectives, integrating insights from the survey and workshop consultations to capture views from academia, industry, policymakers, civil society, and citizens.

Finally, **Section 7** draws conclusions and provides recommendations aimed at policymakers, industry, and the research community to support the responsible development and deployment of liquid electronics.

Annexes complement the analysis by providing the detailed survey instrument.

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2 ETHICAL AND SOCIAL FRAMEWORK

2.1 LONG-TERM ETHICS IN EMERGING TECHNOLOGIES

The ethical assessment of emerging technologies increasingly requires a **long-term perspective** that goes beyond immediate risks and benefits. Technologies at an early stage of development, such as liquid electronics, may take years or decades to mature into commercial products; nevertheless, the decisions made during their design and development strongly influence future impacts. Anticipating ethical and societal implications early is thus essential for responsible innovation.

One of the most relevant approaches in this context is the framework of **Responsible Research and Innovation (RRI)**, promoted by the European Commission, which emphasizes anticipation, inclusion, reflexivity, and responsiveness as guiding principles for research and innovation governance[1]. Long-term ethical reflection encourages developers to consider not only direct applications but also potential **systemic effects**, such as how technology may reshape industries, labour markets, or social practices.

Ethics in emerging technologies is also closely tied to the concept of **anticipatory governance**, which integrates foresight, public engagement, and adaptive regulation to address uncertainty and complexity[2]. For liquid electronics, anticipatory ethics means asking:

What kinds of futures could this technology enable?

Who might benefit, and who might be excluded?

What unintended consequences could arise when liquid-based computing, sensing, or energy systems are scaled up?

Moreover, ethical inquiry must acknowledge that the **pace of technological change often outstrips regulation**. This gap requires proactive assessment of potential risks, including dual-use and misuse scenarios[3]. In the case of liquid electronics, long-term ethics will need to address environmental sustainability, equitable access, and the responsible integration of liquid-based systems into sensitive domains such as healthcare, critical infrastructure, and data-intensive applications.

2.2 ETHICAL PRINCIPLES RELEVANT TO LIQUID ELECTRONICS (SUSTAINABILITY, RESPONSIBILITY, SAFETY, FAIRNESS)

The large-scale production and application of liquid electronics bring forward ethical principles that are central to the governance of emerging technologies. Four principles – **sustainability, responsibility, safety, and fairness** – provide a guiding framework for evaluating both opportunities and risks.

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[1] Stilgoe, J., Owen, R., & Macnaghten, P. (2013). Developing a framework for responsible innovation. Research Policy, 42(9), 1568–1580.

[2] Guston, D. H. (2014). Understanding anticipatory governance. Social Studies of Science, 44(2), 218–242.

[3] Miller, S., & Selgelid, M. J. (2007). Ethical and philosophical consideration of the dual-use dilemma in the biological sciences. Science and Engineering Ethics, 13(4), 523–580.

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- **Sustainability.** Liquid electronics may contribute to sustainability by reducing reliance on rare or toxic raw materials, lowering energy demands, and enabling new forms of energy harvesting. However, the environmental footprint of their production, use, and disposal must be carefully assessed across the entire life cycle[4]. This includes responsible sourcing of raw materials, minimizing waste streams, and ensuring recyclability. The European Green Deal and the EU's Circular Economy Action Plan explicitly call for the integration of sustainability assessments into the design of new technologies[5]. ***For liquid electronics, sustainability means ensuring that novel liquid-based systems align with long-term ecological limits***.

- **Responsibility.** The principle of responsibility requires innovators to anticipate potential societal impacts and engage stakeholders early in the development process[6]. In practice, this means building mechanisms for transparency, accountability, and public dialogue into the governance of liquid electronics. Responsibility is not confined to individual researchers but extends to research institutions, industries, and policymakers who shape how technologies are deployed. ***By embedding RRI practices, liquid electronics can evolve in ways that reflect societal values and expectations.***

- **Safety.** Human health and safety remain critical priorities. Liquid electronics, due to their novel material properties and potential applications in healthcare, wearables, and extreme environments, must undergo rigorous testing to ensure biocompatibility, robustness under stress, and safe end-of-life management[7]. Safety concerns also extend to environmental interactions: accidental leaks, exposure to hazardous solvents, or breakdown in sensitive ecosystems could generate unforeseen harm. ***Precautionary approaches, as embedded in EU legislation on chemicals (REACH), are essential in guiding safe design and deployment***.

- **Fairness.** Fairness relates to **equity, access, and inclusivity** in the distribution of benefits and risks. Without deliberate efforts, disruptive technologies can exacerbate inequalities, concentrating the advantages in well-resourced regions while leaving vulnerable communities behind. **Ensuring fairness in liquid electronics requires addressing global disparities in technology access**, preventing discriminatory applications (e.g., in health or employment contexts), and promoting open standards that support interoperability and affordability. At the same time, fairness implies intergenerational equity: technologies should not compromise the ability of future generations to meet their needs.

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[4] von Schomberg, R. (2013). A vision of responsible innovation. In R. Owen, J. Bessant & M. Heintz (Eds.), Responsible Innovation: Managing the Responsible Emergence of Science and Innovation in Society. Wiley.

[5] European Commission (2020). Circular Economy Action Plan. Brussels.

[6] Owen, R., Macnaghten, P., & Stilgoe, J. (2012). Responsible Research and Innovation: From Science in Society to Science for Society. Science and Public Policy, 39(6), 751–760.

[7] Allhoff, F., Lin, P., & Moore, D. (2010). What is Nanotechnology and Why Does It Matter?. Wiley-Blackwell.

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Taken together, these four principles guided the research and innovation activities of the COgITOR partners: they were embedded into early-stage design and governance of the project implementation to ensure that liquid electronics mature into a field that contributes positively to society and the environment.

2.3 RELEVANT EUROPEAN AND INTERNATIONAL GUIDELINES

The ethical and social implications of liquid electronics must be considered within the broader framework of **European and international guidelines** on responsible science, technology, and innovation. These frameworks provide principles and legal instruments that can guide the responsible development and deployment of emerging technologies.

- **EU Charter of Fundamental Rights (2000/C 364/01)** sets out essential rights that must be respected in research and innovation, including the rights to dignity, freedom, equality, and environmental protection. Articles particularly relevant to liquid electronics include ***Article 1*** (Human dignity), ***Article 3*** (Right to integrity of the person), ***Article 8*** (Data protection), and ***Article 37*** (Environmental protection). These articles emphasize that technological innovations must respect fundamental human values and ensure the protection of individuals and the environment.
- **European Union Frameworks for Responsible Innovation.** The European Commission promotes ***RRI***, which is explicitly referenced in Horizon 2020 and Horizon Europe programmes. RRI emphasizes anticipatory governance, inclusiveness, sustainability, and transparency. These principles are directly relevant to the early-stage design and governance of liquid electronics, particularly regarding sustainability, dual-use risks, and stakeholder engagement.
- **UNESCO** has issued global recommendations that highlight the ethical dimensions of emerging technologies. The **UNESCO Universal Declaration on Bioethics and Human Rights (2005)** stresses principles of human dignity, benefit-sharing, and protection of future generations. More recently, the **UNESCO Recommendation on the Ethics of Artificial Intelligence (2021)** provides guidance on issues such as fairness, transparency, human oversight, and sustainability in disruptive technologies. While focusing on AI, its principles are highly relevant for liquid electronics, which may be integrated into AIoT interfaces.
- The **OECD Guidelines for Multinational Enterprises (2011)** establish standards for responsible business conduct, including transparency, environmental stewardship, and human rights, which apply directly to industries that may commercialize liquid electronics.
- Complementary frameworks include the **UN Sustainable Development Goals (SDGs)**, particularly ***SDG 9*** (Industry, Innovation, and Infrastructure), ***SDG 12*** (Responsible Consumption and Production), and ***SDG 13*** (Climate Action). These goals underline the responsibility of innovators to align technological development with long-term sustainability and social equity.

COgITOR disruptive and cross-sectoral technologies were guided by these European and international frameworks, ensuring that their development respected human rights, supports sustainability, and aligned with global standards of responsible innovation.

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3 LARGE-SCALE PRODUCTION OF LIQUID ELECTRONICS: ETHICAL CHALLENGES

3.1 ENVIRONMENTAL SUSTAINABILITY AND LIFE-CYCLE CONSIDERATIONS

COgITOR always had broader commitment to embed **life cycle thinking and circular economy principles** into the design of liquid electronics. By integrating considerations of resource use, safe production, and potential recyclability from the very beginning, the project aimed to ensure that liquid electronics do not reproduce the environmental pitfalls of conventional silicon-based technologies.

The development of liquid electronics raises important questions about **environmental sustainability** and the **life-cycle impacts** of new materials and devices. Unlike traditional silicon-based electronics, which rely heavily on energy-intensive manufacturing processes and scarce raw materials, ***liquid-state systems such as COgITOR promise new opportunities for sustainable design***. However, their actual contribution to sustainability will depend on careful consideration of the entire life cycle—from raw material sourcing to manufacturing, use, and end-of-life management.

- **Raw materials and resource use.** Many conventional electronic devices rely on critical raw materials such as rare earth elements, which are associated with significant environmental and geopolitical challenges[8]. Liquid electronics, depending on their formulations (e.g., ferrofluids as COgITOR, functional nanoparticles, ionic liquids), may reduce dependence on some of these scarce elements. Nevertheless, the environmental and health impacts of novel colloidal materials and nanostructures must be assessed, especially regarding their toxicity, persistence, and potential bioaccumulation.
  Within the COgITOR project, **PlasmaChem GmbH** plays a central role as the industrial partner responsible for the synthesis of advanced nanomaterials. Among these, **bismuth ferrite (BiFeO3)** has been identified as one of the project KER, due to its unique multiferroic properties and stability under demanding conditions. This material is considered a promising candidate for future applications in electronics, energy harvesting, and spintronics, making it a cornerstone of the liquid electronics concept. At the same time, the development and potential large-scale deployment of BiFeO3 raise important questions about **environmental sustainability and life-cycle impacts**.
  The European Commission has classified bismuth as a material with a moderate supply risk, highlighting concerns around import dependency and limited substitution options. PlasmaChem addressed this challenge by focusing on *synthesis routes that can minimize waste, improve yields, and reduce energy demand*. Traditional high temperature sintering often leads to volatilization of bismuth and the formation of impurities, which lower efficiency and increase environmental burden. To counter these drawbacks, PlasmaChem explored ***greener and more scalable production methods, such as sol-gel and combustion synthesis***.

- **Manufacturing and energy demand.** Electronic manufacturing is among the most energy-intensive industrial processes, contributing to global carbon emissions[9]. ***COgITOR results suggested that liquid-based devices can be fabricated using lower-energy techniques,***

[8] European Commission (2020). Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability. Brussels.
[9] Corcoran, P., & Andrae, A. (2013). Emerging trends in electricity consumption for consumer ICT. IEEE Consumer Electronics Magazine, 2(3), 24–31.

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such as additive manufacturing or chemical synthesis, which could reduce overall environmental impact[10]. At the same time, ensuring that production processes do not generate hazardous chemical by-products or excessive waste streams will be critical.

- **Use phase.** Liquid electronics may offer **energy efficiency advantages**, particularly in low-power, fault-tolerant, and adaptive computing applications. By reducing energy consumption in data processing and sensing, they could contribute to lowering the carbon footprint of digital infrastructures, which is a growing concern in the context of artificial intelligence and big data[11] . In addition, their potential to operate in extreme environments without extensive protective shielding could reduce the resource costs of space or nuclear applications.

- **End-of-life and recyclability.** One of the major sustainability challenges for current electronics is the growing volume of **e-waste**, which exceeded 53Mt in 2019 globally, with only 17% formally recycled[12]. In COgITOR, sustainable ***end-of-life strategies*** were integrated into early design stages, including recyclability of functional liquids, safe disposal of nanomaterials, and potential reusability of hardware components. Approaches such as green chemistry and circular economy principles guided material development to ensure minimal environmental burden.

To systematically evaluate these impacts in the future, **Life-Cycle Assessment (LCA) is recommended as a standard methodology**. LCA enables the quantification of environmental impacts across the stages of material sourcing, production, use, and disposal.

3.2 Human health and safety issues

As liquid electronics transition from laboratory research to potential large-scale applications, **human health and safety** emerge as central ethical and regulatory priorities. The inherently hybrid nature of these systems (combining functional liquids, nanostructured materials, embedded electronics) introduces both new opportunities and new challenges.

COgITOR has ensured safety across the entire life cycle, from synthesis to development, as it is therefore a prerequisite for future deployment and public acceptance.

- **Occupational health and chemical safety.** At the production stage, the synthesis of materials used in COgITOR and liquid electronics at large, such as ferrofluids, ionic liquids, and multiferroic compounds like bismuth ferrite ($BiFeO_3$), involves exposure to nanoparticles, solvents, reactive intermediates. These materials may pose inhalation, dermal, or ingestion risks to workers if proper handling procedures and containment measures are not enforced. European legislation, including *REACH (EC No. 1907/2006)* and the *Chemical Agents Directive (98/24/EC)*, provides the regulatory framework for ensuring worker protection. Under COgITOR, **PlasmaChem GmbH** implements strict laboratory safety protocols and

[10] Chiolerio, A., & Quadrelli, M. B. (2017). Smart fluid systems: The advent of autonomous liquid robotics. Advanced Science, 4(6), 1700036.

[11] Belkhir, L., & Elmeligi, A. (2018). Assessing ICT global emissions footprint: Trends to 2040 & recommendations. Journal of Cleaner Production, 177, 448–463.

[12] Baldé, C. P., Forti, V., Gray, V., Kuehr, R., & Stegmann, P. (2020). The Global E-waste Monitor 2020. United Nations University (UNU).

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closed-system syntheses to minimize emissions and accidental releases during nanoparticle (bismuth ferrite) production and handling.

- **Toxicological and biocompatibility considerations.** Liquid electronics may be used in close contact with biological systems, for example, in wearable sensors, soft robotics, or biomedical monitoring devices. This raises questions about the biocompatibility of the materials used, their degradation products, and their potential to enter the human body through skin contact or accidental exposure. While materials like $BiFeO_3$ are generally considered non-toxic and environmentally stable, impurities, dopants, or solvent residues introduced during synthesis could alter their safety profile. In the case COgITOR will be applied in the biomedical field, comprehensive **toxicological screening** and **surface characterization** are therefore essential to confirm chemical stability and prevent leaching of hazardous ions.

- **Thermal, electrical, and mechanical safety.** In operation, liquid electronics may involve thermal gradients, electric fields, or mechanical actuation, all of which can pose hazards if systems malfunction or are improperly insulated.

- **End-of-life safety.** Improper disposal of functional liquids or nanomaterials could lead to contamination of water or soil, with possible effects on human health through bioaccumulation or food chain exposure. The European *Waste Framework Directive (2008/98/EC)* mandates the safe treatment of hazardous waste, including electronic waste containing nanoparticles. Circular management strategies, such as controlled recovery of bismuth and iron from BiFeO3-based materials will help minimize potential health and environmental risks.

3.2 RESPONSIBLE SOURCING OF MATERIALS AND SUPPLY CHAIN ETHICS

The emerging field of liquid electronics relies on a variety of functional materials, ranging from **metal oxides and ferrofluids to polymers, ionic liquids, and nanoparticles**, which together enable the combination of sensing, computing, and energy-harvesting functionalities within a fluid medium. As this technology progresses from laboratory prototypes to potential industrial production, the **ethical implications of sourcing and supply chain management** become increasingly significant. Ensuring transparency, social responsibility, and environmental integrity along the entire value chain is essential to align innovation with European and international sustainability goals.

- **Critical raw materials and geopolitical dependency.** Many of the base elements used in liquid electronics—such as **bismuth, iron, titanium, or rare earth dopants**—are listed among the *EU's critical raw materials (CRM),* owing to their limited availability and concentrated production outside Europe[13]. Bismuth, used in the synthesis of **bismuth ferrite ($BiFeO_3$)** developed within COgITOR, is largely mined as a by-product of lead, copper, tungsten production, with China accounting for over 70% of global supply. This dependency

[13] European Commission (2023). *Critical Raw Materials Act: Ensuring a Secure and Sustainable Supply of Critical Raw Materials in Europe*. Brussels.

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introduces both **geopolitical and ethical risks**, including potential exposure to supply disruptions, market volatility, and variations in environmental and labour standards across producing countries[14].
To mitigate these challenges, **responsible sourcing strategies should be embedded early in the liquid electronics value chain**. These include the adoption of certified sourcing standards, such as the *OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas (2016)* and traceability mechanisms that document the origin, extraction methods, and environmental performance of input materials.

- **Environmental and social responsibility in material extraction.** The mining and processing of metal oxides can generate significant **environmental and social impacts**, including land degradation, water contamination, and unsafe working conditions. For COgITOR, the emphasis on **green chemistry** and **low-impact synthesis methods**—pursued by partners such as **PlasmaChem**—is an important step toward reducing the reliance on environmentally damaging supply chains. By focusing on chemical routes that minimize energy use and hazardous waste, the project contributes to the **de-materialisation** of electronics and the ethical management of raw material inputs.

- **Circular economy and secondary sourcing.** A central pillar of responsible sourcing is the transition from linear to **circular material flows**. For liquid electronics, this means prioritizing the **reuse and recovery** of valuable elements such as bismuth and iron from production waste and end-of-life devices. The integration of Life-Cycle Assessment (LCA) within COgITOR will enables early identification of recovery potential and recycling pathways, even for complex oxide systems. Secondary sourcing from industrial by-products or urban mining can further reduce environmental footprints and strengthen Europe's strategic autonomy.

- **Supply chain transparency and ethical governance.** Responsible supply chains also depend on **transparency, accountability, and human rights protection**. Companies involved in material production and device manufacturing are increasingly expected to comply with the *EU Corporate Sustainability Due Diligence Directive (2024)*, which mandates that businesses identify, prevent, and mitigate adverse environmental and social impacts throughout their supply chains. For liquid electronics, this entails verifying supplier compliance with international standards on labour conditions, environmental management, and anti-corruption practices. Digital traceability tools—such as blockchain-based material passports—can support this process by enhancing data sharing and verification.
- **Localisation and resilience.** In line with the EU's *Raw Materials Act (2023),* establishing resilient and ethical supply chains also involves fostering **local and regional production capacities** for strategic materials. COgITOR's collaboration between research institutes and industrial actors such as PlasmaChem provides a model for **European-scale innovation ecosystems**, where responsible sourcing, sustainable material synthesis, and ethical supply

[14] Blengini, G. A., et al. (2020). *Stud999y on the EU's list of Critical Raw Materials – Final Report (2020)*. European Commission, DG GROW.

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chain practices are integrated from the outset. This approach not only mitigates risk but also contributes to Europe's broader objectives of environmental protection, strategic autonomy, and social justice.

3.3 END-OF-LIFE MANAGEMENT AND RECYCLABILITY

COGITOR introduces a new class of *liquid electronics* and *colloidal cybernetic systems* (CCS), which differ fundamentally from conventional solid-state devices in both structure and lifecycle profile. Their end-of-life (EoL) management strategy is therefore based on the sustainability principles already embedded in the project design and verified through WP6 exploitation deliverables and IIT's patent documentation.

- **Circular Design Principles.** From the outset, the COGITOR consortium—particularly IIT, EMPA and PlasmaChem—adopted a **design-for-disassembly** and **non-critical materials** approach. All subsystems, including the *liquid state-in-memory computing system* and *soft thermogalvanic energy harvester*, employ recyclable and non-toxic constituents:
    - Liquids and electrolytes are **water-based or hydrogel-based**, containing functional nanoparticles (e.g. $BiFeO_3$, TiN, Fe_3O_4) that are stable, non-rare, and recoverable through filtration and precipitation techniques.
    - Encapsulation materials, such as the self-healing polymer skins, are **silicone- or polyurethane-derived elastomers designed for mechanical reusability**. Their cross-linked networks allow *thermo-reversible reshaping*, enabling mechanical recycling or controlled depolymerisation at end-of-life.
    - Electronic modules (Dandelium ICs**)** and connectors follow **standard RoHS-compliant component design**, facilitating separation of metals (Cu, Al) and printed circuit substrates during recycling streams.

- **Recovery and Reuse Pathways.** The main EoL pathway for COGITOR subsystems involves **material recovery and regeneration** rather than disposal:
    - **Liquid phase reclamation** – The colloidal or hydrogel media can be regenerated by solvent exchange and re-dispersion of nanoparticles. EMPA and PlasmaChem demonstrated recovery of $BiFeO_3$ and other oxides at lab scale without degradation of performance.
    - **Polymer and casing recycling** – Self-healing skins are mechanically robust and recyclable; fragments can be reprocessed into new devices or down-cycled into industrial sealants.
    - **Metal and electronics recycling** – Aluminium housings, copper coils, and PCB traces are compatible with existing electronics waste treatment systems.
    - **Hybrid component remanufacturing** – Liquid electronics modules can be drained, sterilised, and refilled with fresh functional fluids, enabling reconditioning rather than replacement, extending lifetime and reducing raw material demand.

- **Environmental and Safety Considerations.** All materials have been screened for REACH compliance and are free from toxic heavy metals or halogenated solvents. The quasi-solid hydrogel electrolytes are biodegradable under controlled conditions, while ferroelectric nanoparticles are chemically inert. During decommissioning, no harmful vapours or residues would be generated.

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- **Recyclability and Future Standardisation.** The COGITOR system contributes to establishing **new standards for recyclable liquid electronics** by demonstrating:
  - closed-loop recovery of colloidal media;
  - modular replacement of energy harvesting and memory units;
  - use of biodegradable or reprocessable encapsulants;
  - RoHS- and WEEE-aligned component segregation.

These features ensure that future upscaling—e.g. through the planned spin-off—will comply with EU circular economy directives and align with SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action).

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4 SOCIAL IMPLICATIONS

4.1 IMPACT ON EMPLOYMENT AND SKILLS (WORKFORCE TRANSFORMATION)

The transition towards advanced systems such as those envisaged by the COGITOR project—encompassing liquid-electronics and colloidal cybernetic modules—carries profound implications for the European workforce. It is not just a matter of new technologies, but of **how** employment, skills and roles are transformed across multiple layers: manufacturing, ICT, materials, service/support and continuous learning.

In the Eurostat data for 2022, employment in the EU's manufacturing sector (NACE Section C) stood around 30 million persons (~18.7 % of the business economy's employment) with value-added of €2.4 trillion[15]. This baseline is relevant because COGITOR's value chain spans manufacturing of new material systems, integration of electronics and deployment in circular-economy contexts.

Meanwhile, the ICT sector (services + manufacturing) has grown significantly in terms of value-added: in 2022 it accounted for about 5.5 % of EU gross value added[16]. More specifically, employment of ICT specialists in the EU reached over 10 million in 2025 and has been rising steadily[17].

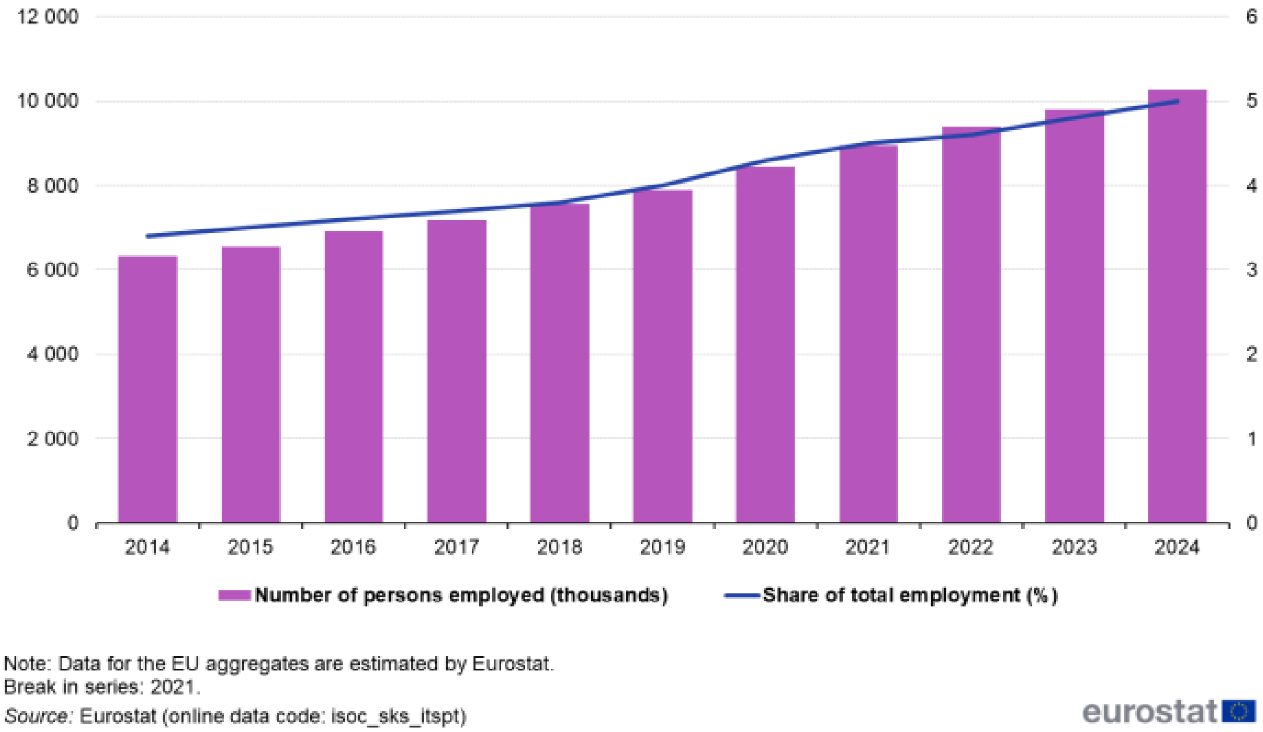

Figure 2. ICT specialists, EU, 2014-2024

[15] https://ec.europa.eu/eurostat/statistics-explained/index.php?oldid=625731
[16] https://ec.europa.eu/eurostat/statistics-explained/index.php?oldid=673052
[17] https://ec.europa.eu/eurostat/web/interactive-publications/digitalisation-2025

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A key aspect of workforce transformation is the shift in **skills demand**. According to Eurostat's "Skills for the digital age" overview[18]:

- In 2023, 56% of EU adults (aged 16-74) had at least basic digital skills.
- The EU target for 2030 is that at least 80% of adults should have at least basic digital skills.
- On education attainment: individuals with higher formal education have markedly higher digital-skills levels.

Additionally, the Eurostat "Employment statistics – utilisation of job skills" module[19] shows that tasks requiring digital devices, complex calculations or reading work-related documents have significant prevalence: for example, in 2022 a non-negligible share of employed persons used digital devices for most of their working time.

The transformation of Europe's industrial and research landscape toward intelligent, sustainable, and cybernetic systems has direct consequences for how COGITOR will shape and interact with the workforce. The project's technological ambition—introducing liquid electronics, self-healing materials, and autonomous cybernetic architectures—requires not only scientific innovation but also a profound shift in the composition and capability of the people who design, manufacture, and manage these systems.

In this context, COGITOR represents a driver of **new forms of employment** that blend materials science, information technology, and sustainability. The project will create demand for interdisciplinary profiles that combine expertise in nanomaterials, soft electronics, and artificial intelligence with a strong awareness of circular-economy principles. These emerging job categories will not replace traditional manufacturing roles but will evolve from them, leading to a re-definition of existing occupations. Technicians and engineers in conventional electronics manufacturing, for instance, will need to transition toward hybrid skills that include data-driven diagnostics, handling of soft polymeric and colloidal materials, and operation of adaptive, AI-enabled systems.

The project's emphasis on **gender balance and inclusivity** also aligns with broader European workforce priorities. At present, women account for less than 20 % of ICT specialists in the EU, according to Eurostat's 2024 data. By integrating equal-opportunity recruitment policies and mentoring initiatives within its spin-off and research training activities, COGITOR can help close this gap and diversify the technological workforce that will carry liquid cybernetics into industrial deployment.

Another strategic implication concerns **regional cohesion and capacity building**. Digital transformation is progressing unevenly across Europe, with northern and western Member States showing digital-skills attainment rates of 75–85 %, compared with less than 40 % in some southern and eastern regions. By conducting demonstration and training initiatives in collaboration with small and medium-sized enterprises (SMEs) and innovation hubs located in regions of intermediate technological readiness, COGITOR can directly contribute to narrowing this divide. Such an

[18] https://ec.europa.eu/eurostat/statistics-explained/index.php?oldid=685132
[19] https://ec.europa.eu/eurostat/statistics-explained/index.php?oldid=605406

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approach will also strengthen local innovation ecosystems, making them better prepared to adopt and exploit COGITOR's results after the project's completion.

4.2 SOCIETAL ACCEPTANCE AND TRUST IN LIQUID-STATE TECHNOLOGIES

The transition to innovative systems like liquid-state electronics—as envisaged by the COGITOR project—cannot rest solely on technical breakthroughs: it fundamentally depends on how society perceives and trusts these technologies. While much of the public discussion so far has centred on more familiar technologies such as artificial intelligence or renewable energy, the same patterns of acceptance, trust, perceived risks and benefits are highly relevant for emerging fields such as liquid-state electronics and colloidal cyber-systems.

Empirical research shows that trust and perceptions of risk and benefit are pivotal determinants of whether new technologies are accepted by society. For example, a study of laypeople's mental models reveals a very strong correlation ($r^2 \approx 0.89$) between perceived risk and overall valuation of technology: the higher the perceived risk, the lower the perceived value[20]. Moreover, comparative studies of public attitudes toward novel technologies emphasise factors such as familiarity, transparency of governance, and the clarity of communicated benefits[21].

In the specific context of liquid‑state electronics, societal acceptance will turn on several inter-related dimensions. First, the **visibility and intelligibility** of the technology matter: unlike traditional solid‑state electronics, liquid electronics may appear more unfamiliar or abstract to end-users and lay citizens. This unfamiliarity can elevate perceived risks—especially around safety, reliability, and environmental impact—which research identifies as critical impediments to acceptance. The classic work on public perceptions of new technologies highlights that when a technology is seen as involuntary (i.e., imposed rather than chosen), uncontrollable, or unfamiliar, the tolerance for any risk is significantly lower[22].

Second, **trust in institutions, governance and material transparency** becomes central. For citizens to accept liquid electronics, they must believe that the materials (for example, colloids, nanomaterials) and the systems are managed responsibly—both in everyday use and at end‑of‑life. The broader literature on trust in technology underscores that credibility of regulatory frameworks, clarity of roles and accountability, and openness of communication all influence acceptance[23]. For instance, one global study reported that only 46% of people were willing to trust AI systems in general, while 70% believed strong regulation was required—a pattern that signals the wider need for robust governance in emerging technologies[24].

Third, societal acceptance is shaped by the **perceived benefits and sustainability credentials** of the technology. Liquid electronics promise new functionalities—flexibility, adaptability, recyclability—but unless those benefits are clearly communicated, the public may focus instead on unknowns (e.g.,

[20] https://link.springer.com/article/10.1007/s44206-024-00148-5
[21] https://www.sciencedirect.com/science/article/pii/S0160791X23001082
[22] https://www.jstor.org/stable/4314956
[23] https://www.sciencedirect.com/science/article/pii/S0040162525001623
[24] https://kpmg.com/xx/en/our-insights/ai-and-technology/trust-attitudes-and-use-of-ai.html

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potential hazards of novel materials, reliability questions). Studies of energy - technologies demonstrate that perceived benefits help offset perceived risks and boost social acceptance.

For COGITOR specifically, building societal trust around liquid - state systems means engaging proactively with citizens, industry stakeholders and policy-makers. The project must emphasise transparent material flows, safe manufacturing and end - of - life strategies (such as recyclability), and integrate public dialogues that surface concerns and knowledge gaps. It also means presenting real-world applications and benefits in relatable form: explaining how these systems might enable safer, more sustainable electronics, what happens when devices reach end-of-life, and how participants (workers, consumers, local communities) are exposed or protected.

Over time, this approach can transform unfamiliar "liquid electronics" from a niche engineering concept into a trustworthy component of the broader circular-economy narrative. Yet the history of innovation warns us: if public trust is weak or if technology emerges without adequate explanation and inclusion of societal values, acceptance may lag, adoption may stall or backlash may emerge.

4.3 ETHICAL ISSUES IN HUMAN–MACHINE INTERACTION

The advent of *liquid electronics* and *CCS* in COgITOR raises ethical questions concerning how humans and intelligent, adaptive materials will interact. Unlike conventional rigid systems, COgITOR's liquid-state technologies possess emergent behaviors—self-healing, fault-tolerant, and learning capabilities—that blur boundaries between machine autonomy and human control. These properties require a rethinking of ethical principles related to **agency, transparency, safety, and responsibility** in human–machine relations.

At the core of this discussion is the concept of **distributed cognition** within the liquid medium. COgITOR's neuromorphic and self-organizing liquids—capable of learning and adapting—extend human decision-making into the material substrate itself. This shift from human-centered control to co-evolving human–material systems needs ethical safeguards ensuring that decision processes remain understandable and auditable. The project's *holonomic architecture* (liquid memory and in-memory computing) allows information to be encoded throughout the fluid volume, which challenges traditional accountability models where discrete computational nodes can be monitored or isolated.

From an ethical standpoint, **transparency and explainability** are critical. In AI and adaptive electronics, opacity already limits human oversight; in COgITOR's case, the dynamic and amorphous nature of the medium may further obscure causal chains between input and response. Therefore, ethical design must ensure "traceability" of actions—documenting stimuli, environmental conditions, and computational outcomes to maintain scientific integrity and user trust. This aligns with Horizon Europe's AI ethics framework emphasizing human agency and oversight[25].

Safety and reliability represent another major axis of concern. Liquid-state systems designed for extreme environments—such as medical, aerospace, or industrial settings—must comply with evolving safety standards and ethical norms on *non-maleficence*. As outlined in the COgITOR Grant Agreement and subsequent exploitation plans, the project employs non-toxic, non-rare materials and self-healing polymers precisely to minimize environmental and human health risks. However, ethical

[25] European Commission, *Ethics Guidelines for Trustworthy AI*, 2019

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evaluation must extend beyond materials to encompass system behavior: how the machine reacts to unpredicted stimuli, self-repairs, or reconfigures under failure conditions. The project therefore integrates ethical risk assessment into testing protocols under WP5 (“Self-healing and fault-tolerance testing”).

Data ethics also play a role. The *tomographic microwave impedance spectroscopy* (MIS) system, which reads and writes within the liquid processor, collects high-frequency electromagnetic and environmental data. While the data are not personal in the conventional sense, the European General Data Protection Regulation (GDPR) principles on data minimization and transparency are relevant for potential future biomedical or monitoring uses.

4.4 INEQUALITIES, ACCESSIBILITY, AND INCLUSION

The development of *liquid electronics* within the COgITOR project represents not only a technological breakthrough but also a potential catalyst for greater **accessibility and inclusion** in emerging digital and scientific ecosystems. However, as with any advanced innovation, its deployment must be critically examined to ensure that it does not reproduce or exacerbate existing **inequalities** in access to technology, knowledge, and opportunity.

Liquid electronic systems—based on flexible, self-healing, low-cost materials—introduce the possibility of **democratizing access** to high-performance computing, sensing and energy systems. Unlike traditional silicon-based technologies, which rely on rare materials, expensive fabrication, and rigid infrastructures, *liquid-state devices can be produced using scalable, eco-friendly processes with non-toxic and widely available components.* This structural shift toward affordability and sustainability opens the door to applications in **low-resource settings**, where current hardware is cost-prohibitive or environmentally unsuitable. For instance, soft thermogalvanic cells and self-healing skins developed within COgITOR could be integrated into wearable health monitors, prosthetics, or environmental sensors that are lightweight, biocompatible, and reusable—addressing accessibility in both economic and physical terms.

However, the **digital divide** extends beyond the cost of devices. As COgITOR technologies become embedded in future cybernetic systems, disparities in education, technical literacy and research participation may widen between well-equipped institutions and underrepresented regions. To counter this, COgITOR’s exploitation and dissemination strategies emphasized **open science and knowledge transfer**, including public deliverables, training workshops, and collaborative exploitation models. These measures are intended to distribute the benefits of liquid electronics beyond a small circle of industrial and academic elites, fostering equitable access to both the knowledge base and the resulting products.

From a **disability inclusion** perspective, liquid electronics introduce new pathways toward human–machine interfaces that are adaptive, ergonomic, and responsive to individual physical diversity. Flexible and soft-state sensors could enable assistive devices that conform to the user’s body, restore sensory feedback, or support prosthetic control systems designed for personalized use. The project’s outreach commitments—such as incorporating audio descriptions into public communication, as stated in the WP6 dissemination plan—reflect a broader ethic of accessibility not only in technology design but also in knowledge sharing and stakeholder engagement.

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Nevertheless, inclusion also requires vigilance regarding **algorithmic and material bias**. As COgITOR systems evolve into self-learning and autonomous configurations, designers must ensure that adaptive behaviors do not privilege certain operational contexts, users, or data profiles over others. Ethical and inclusive design thus extends into the computational architecture itself, demanding transparency, human oversight, and participatory testing across diverse user groups.

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5 REGULATORY AND GOVERNANCE ASPECTS

5.1 CURRENT REGULATORY FRAMEWORKS AND GAPS

The regulatory landscape for **liquid electronics**—encompassing CCSs, liquid-state computing, self-healing materials and energy-harvesting fluids—is still in its infancy. Current frameworks in the European Union and internationally were designed primarily for **solid-state electronic devices, nanomaterials and chemical substances**, which do not fully address the hybrid physical-chemical and cybernetic nature of liquid systems such as those developed in **COgITOR**.

At present, the applicable regulations derive from multiple domains rather than a dedicated directive. From the **chemical and materials standpoint**, liquid-state electronic components are partially regulated by the *REACH Regulation (EC No. 1907/2006)* and the *CLP Regulation (EC No. 1272/2008)*, which ensure the registration, evaluation, and safe use of chemicals. For instance, the bismuth ferrite nanoparticles and hydrogel-based electrolytes used in COgITOR's systems must comply with REACH and associated safety assessments before upscaling to industrial production. However, these regulations are tailored to static substances and do not yet cover **dynamic, reconfigurable materials** capable of computation, self-healing, or autonomous adaptation.

From an **electronics and data processing** perspective, liquid computing systems that perform sensing, storage and decision-making functions would theoretically fall under the *Radio Equipment Directive (RED) 2014/53/EU*, the *Electromagnetic Compatibility Directive (EMC) 2014/30/EU*, and potentially under the *Artificial Intelligence Act* recently proposed by the European Commission (COM/2021/206). Yet, none of these instruments explicitly accounts for **non-silicon, bioinspired, or fluidic computing architectures**. In COgITOR's case, the Dandelium integrated circuit operating within a liquid medium constitutes a "non-standard computing substrate," for which no certification or conformity assessment procedures currently exist.

In the **medical and wearable applications** foreseen for self-healing skins or soft thermogalvanic cells, regulation may intersect with the *Medical Device Regulation (EU) 2017/745* and *ISO 10993* standards for biocompatibility testing. Nevertheless, these frameworks presuppose stable, solid materials, not morphologically variable systems that continuously change composition or structure in operation. Similarly, **waste management and end-of-life directives**, including the *WEEE (2012/19/EU)* and *RoHS (2011/65/EU)* directives, lack provisions for the recycling and recovery of **liquid-based electronics**, which may combine polymers, solvents, nanoparticles, and embedded circuits.

In terms of **nanomaterials governance**, the European Chemicals Agency (ECHA) has begun adapting guidance to emerging materials, yet **liquid-phase nanostructured electronics** blur the line between device and substance, posing classification challenges. The dynamic properties of colloidal systems—capable of switching phases, reacting to stimuli, or reconfiguring—defy existing categorizations in product safety and environmental law. As identified in COgITOR's stakeholder and exploitation analyses, one of the major risks for technology uptake is the **absence of standardization and legal recognition** of "liquid-state electronic devices" as a product class.

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The **main regulatory gaps** can therefore be summarized as follows:

1. **Absence of product classification**: No harmonized standards or CE marking procedures exist for devices where electronic, chemical, and mechanical domains coexist dynamically (e.g., self-healing skins or liquid processors).
2. **Insufficient safety and environmental guidelines**: Existing chemical and waste frameworks lack methodologies to evaluate environmental persistence, recyclability, or toxicity of functional liquids.
3. **Lack of conformity procedures for adaptive computing media**: Current EMC and AI conformity assessments presume deterministic, stable architectures.
4. **Limited ethical and data-protection frameworks** for materials that sense, learn, or store information in a physical substrate.
5. **No lifecycle standards** for hybrid systems that blur the boundary between consumable materials and durable electronics.

Bridging these gaps will require **cross-domain regulatory innovation**, combining chemical safety, AI governance, and electronic device certification. COgITOR contributes by providing experimental data for safe materials integration and proposing new **standardization pathways** for “liquid-state cybernetic systems,” aligned with the EU’s **Responsible Research and Innovation (RRI)** principles. The development of such frameworks will be crucial for enabling market entry, ensuring user safety, and maintaining European leadership in this emerging technological domain.

5.2 RECOMMENDATIONS FOR GOVERNANCE

The rapid emergence of **liquid electronics** demands a forward-looking governance model that bridges materials regulation, digital policy, and sustainability frameworks. Unlike traditional solid-state devices, these systems merge **dynamic chemical, electronic, and computational functions**, challenging existing certification and standardization pathways.

Governance should adopt a **multi-layered, anticipatory approach**. At the European level, coordination between **ECHA**, **CENELEC**, and **ISO technical committees** is essential to create a shared vocabulary and classification system for liquid-state devices. The EU’s Responsible **Research and Innovation (RRI)** framework and the proposed **AI Act** should explicitly include adaptive, bioinspired, and fluidic systems, establishing criteria for transparency, safety, and explainability in materials that perform computational tasks. Public agencies could support the creation of a **“Liquid Technologies Observatory”** to monitor risks and guide ethical deployment, similar to nanotechnology governance models.

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6 STAKEHOLDER PERSPECTIVES

6.1 THE SURVEY

6.1.1 Overall survey design

In the last 20 years many textbooks were published on survey methodology. Groves et al.[26] provide a good overview on the whole process from the design to the analysis and interpretation. In addition, there is several specific literatures on various data collection modes, testing questionnaires and questions, interviewing strategies etc. Based on those, we approached the COgITOR survey with a systematic approach with 3 main operational phases – Planning, Operation, Evaluation (Figure 3).

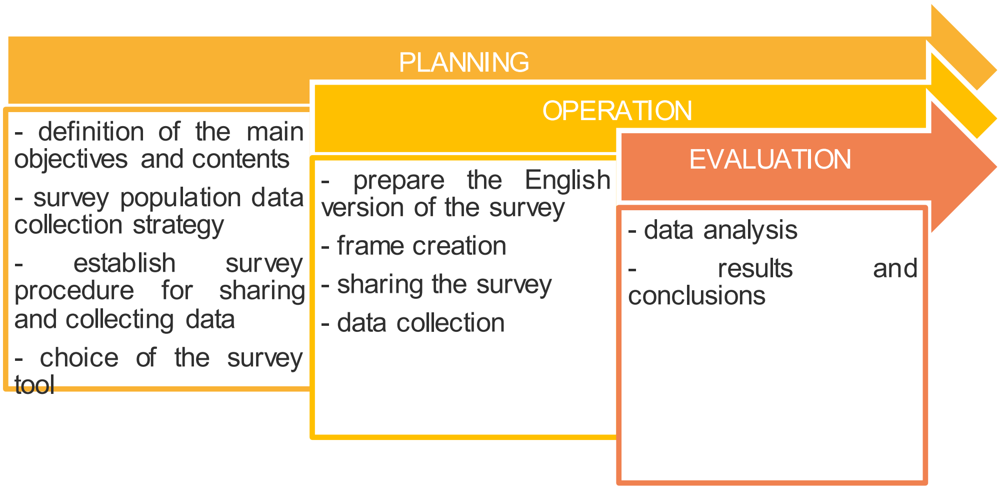

Figure 3 Operational phases of the survey process design

The survey was prepared in English with the *EUsurvey tool*[27] and conducted in accordance with the EU GDPR.

The survey is composed of 3 sections:

- the “Introduction”: a brief introduction of COgITOR project, with description of the consortium and main objective of the project and the survey, is displayed.
- the “Disclaimer”: only if the responders agree with the *Private Statement Consent*, they can see the 3rd section, otherwise they end up the survey.
- the “Survey”, with mandatory questions divided into:
    - general questions about the participant profile;
    - awareness and perception of liquid electronics;

[26] Groves R.M., Fowler F.J., Couper M.P., Lepkowski J.M., Singer E. & Tourangeau R. (2004). Survey Methodology. Hoboken: John Wiley & Sons

[27] https://ec.europa.eu/eusurvey/home/welcome

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- ethical considerations and social implications;
- governance recommendations;
- forward looking vision;
- conclusion.

The full survey is reported in Annex I.

6.2 DATA COLLECTION AND ANALYSIS OF RESULTS

A champion chest of 29 responders replied to the survey: among them, only 28 provided their consent and replied to the survey, one did not provide their consent. Thus, the useful replies analysed in this sub-section are 28.

Responders are mainly from public or private *RTOs* and *university (79%)* while only a small percentage is represented by *SME* (Figure 4).

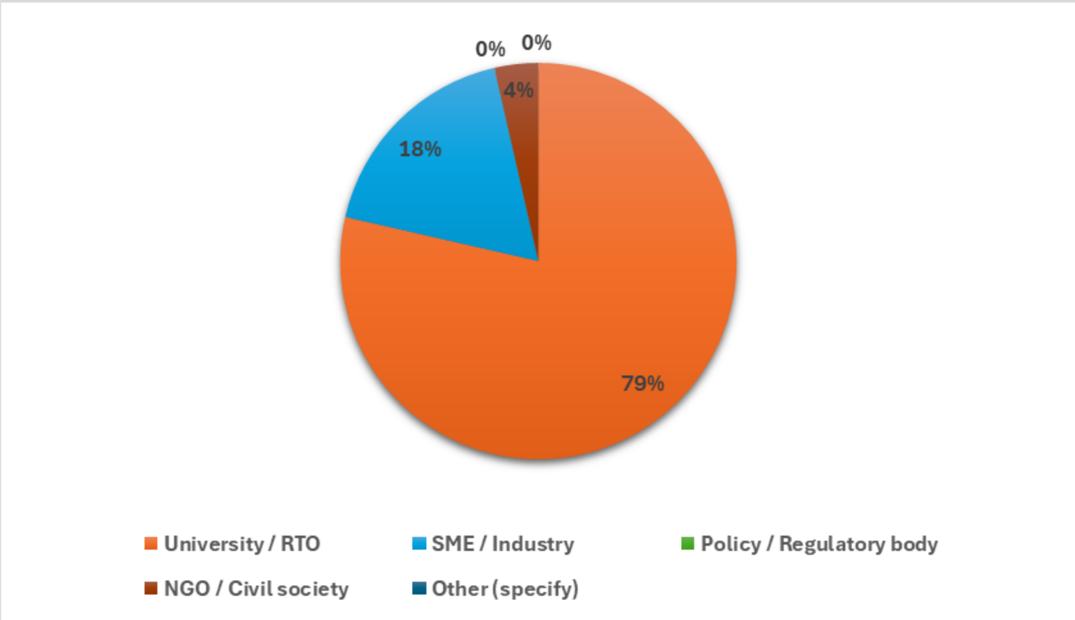

Figure 4 Type of responders' organizations.

Responders are mainly from the "*materials"* and "*computing*" scientific fields. Other responders are in the field of maths, physics, environmental energy. *Half of them* has declared that they already have previous experience with liquid-state or unconventional electronics.

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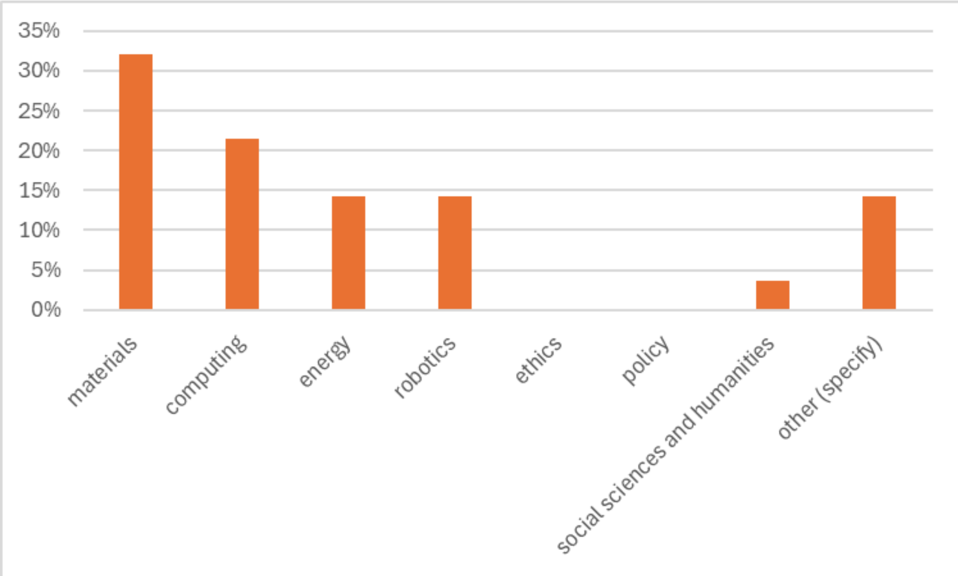

Figure 5 Field of expertise.

It seems that 1/3 of responders are familiar with the *concept of liquid electronics* (*35%)* while others not, confirming that the liquid electronics is still a not well-known field with respect to solid state electronics.

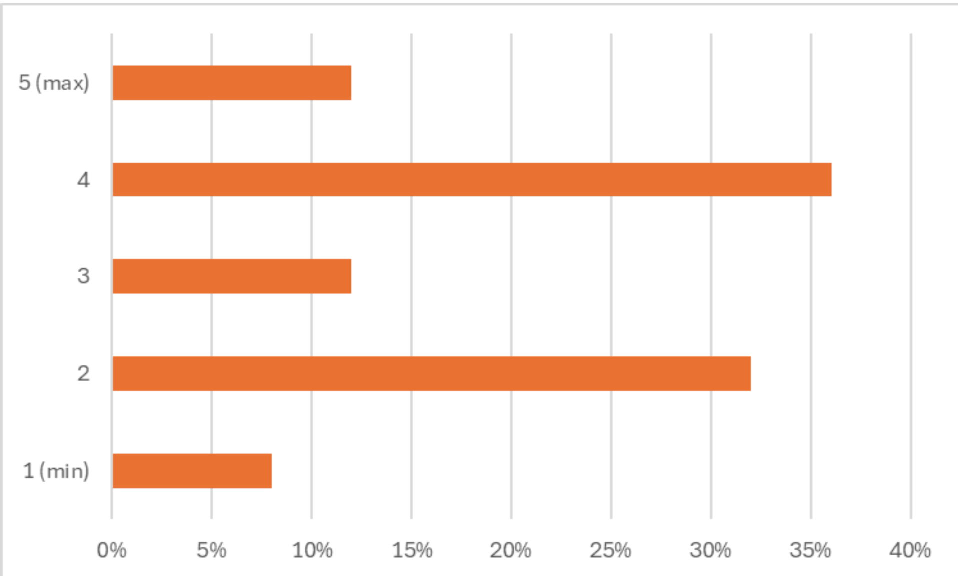

Figure 6 Level of literacy about the liquid electronics.

Nevertheless, their initial perception of the societal potential of liquid electronics is *moderately high (scores 4 and 5)*.

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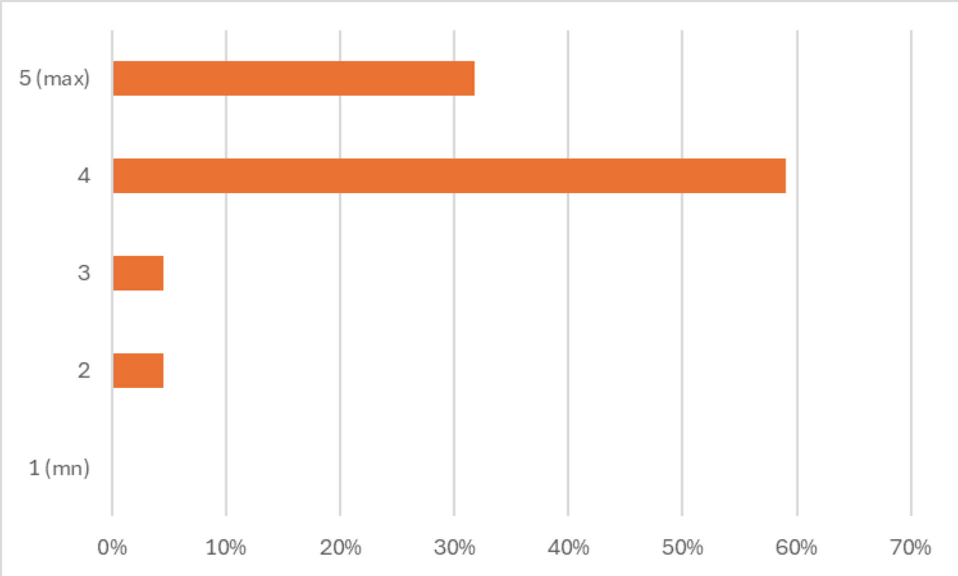

Figure 7 Initial perception of social implications of liquid electronics.

Robotics & Automation is the most voted (35%) application relevant for liquid electronics, followed by Energy harvesting & Storage and Healthcare & Implants (both around 20%). Other is specifically focused on AI.

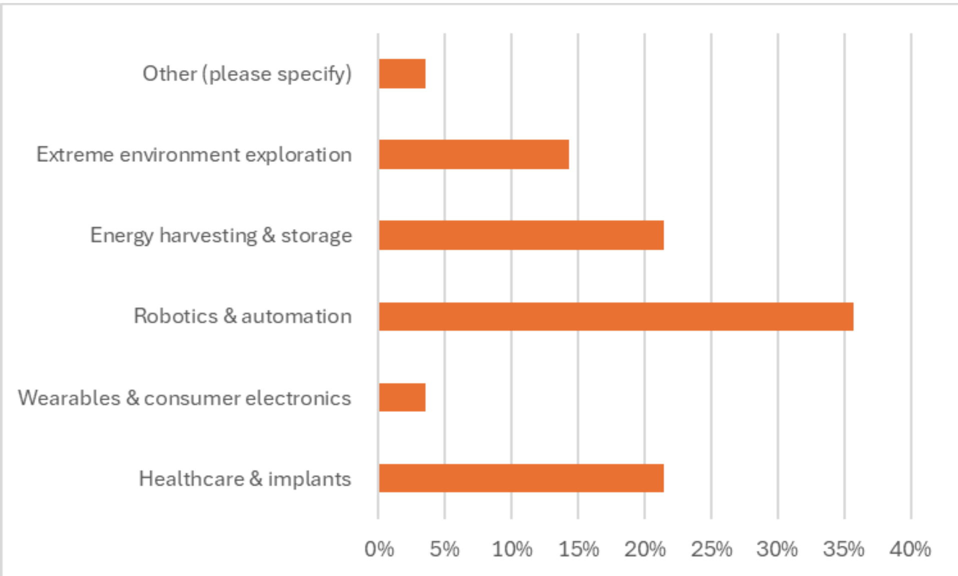

Figure 8 Applications of liquid robotics.

Responders were asked to rate their levels of concern from different points of view on liquid electronics as reported in the following table. The average rating is around *3*, suggesting that respondents are uncertain about whether and what kind of concerns liquid electronics might raise. Only *dual-use issues* emerged as the main area of concern.

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Table 1. Level of concerns

	Environmental sustainability (materials, recyclability, waste)	Human health and safety	Data privacy and human–machine interaction (e.g., implants, wearables)	Equity and accessibility (who benefits, who is excluded)	Dual-use risks and misuse (e.g., surveillance, military)
1 (min)	7%	7%	25%	14%	7%
2	25%	29%	18%	25%	4%
3	**36%**	**32%**	**32%**	**32%**	29%
4	18%	18%	11%	21%	25%
5 (max)	14%	14%	14%	7%	**36%**

The respondents interpreted the term "concern" primarily as referring to worries or perceived risks associated with the technology, rather than mere interest. Their main interests focused on the potential for *low-energy edge computing*, especially for exploring extreme environments and developing computational processes with reconfigurable or soft materials, which could be compatible with biological systems. These applications were seen as promising for fields such as tissue engineering and environmental monitoring. However, the main concerns raised related to possible *military uses* of the technology and broader issues of fairness in the innovation value chain. Respondents also highlighted the importance of *transparency from manufacturers* regarding risks, privacy issues, and the need for equitable intellectual property management to avoid limiting the technology's diffusion. Environmental impact was a lesser concern, though some mentioned the importance of monitoring the *disposal and supply of chemical components at the device's end of life*, especially given uncertainties about potential hazards in liquid electronics.

The respondents identified a range of **potential positive social impacts** from the large-scale adoption of liquid electronics. Key anticipated benefits include *greater accessibility to advanced, quantum-like computing at lower costs, which could make technology more inclusive and human-centred.* Many highlighted *improved efficiency, energy savings*, and *adaptability* to changing environmental conditions as major advantages. Some believed this technology could drive significant economic growth, particularly within the EU, by enabling a wider range of applications and fostering innovation. Several responses pointed to improvements in healthcare, such as the development of *new, affordable diagnostic methods and enhanced medical devices, including better prosthetics and interfaces with biological systems*. The technology was also linked to environmental sustainability, with suggestions of *reduced electronic waste, sustainable computing solutions, and the potential for large-scale environmental monitoring and assessment*. Other anticipated impacts include reduced reliance on a small number of countries for electronic components, increased resilience through backup data storage, and potential for robots to take over certain tasks. Some respondents, however, felt it was too early to predict concrete social impacts, while a few expressed uncertainties or did not know what to expect.

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Transparency and *safety for consumers* are the factors that most influence public acceptance of liquid electronics from responders' points of view.

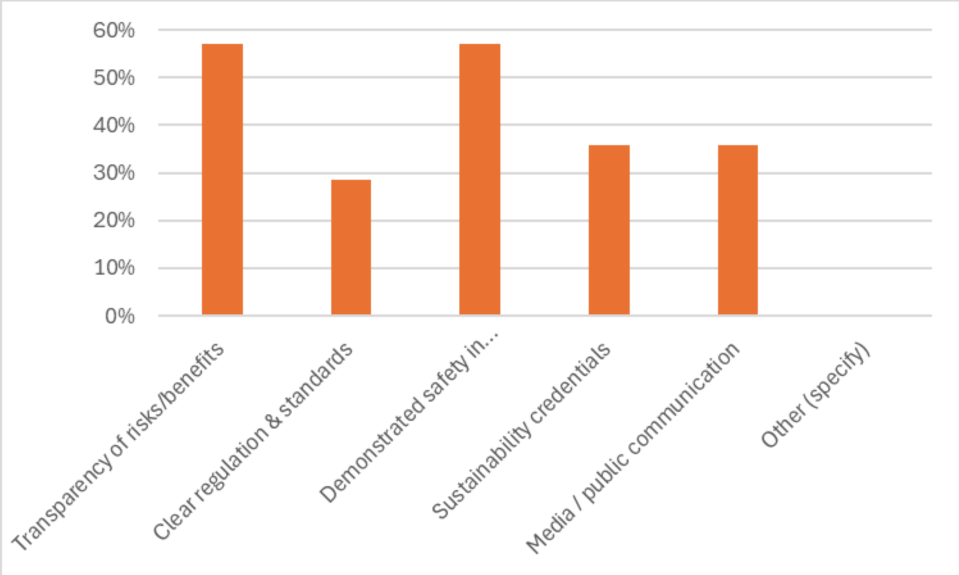

Figure 9 Factors that influence public acceptance of liquid electronics.

The respondents did not comment on how adequate current regulatory frameworks are for dealing with such technologies. This aligns with the gaps highlighted in Section 5.

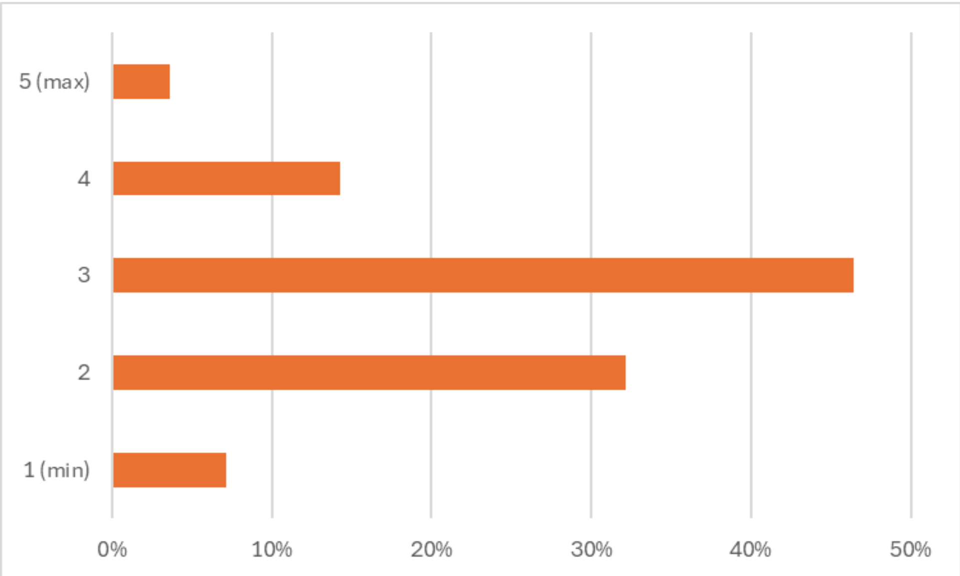

Figure 10 Perception of adequateness of current regulatory frameworks for liquid electronics.

However, the *68%* indicate that the first type of governance mechanism to be prioritized in liquid electronics is *Open science & Transparency requirements*.

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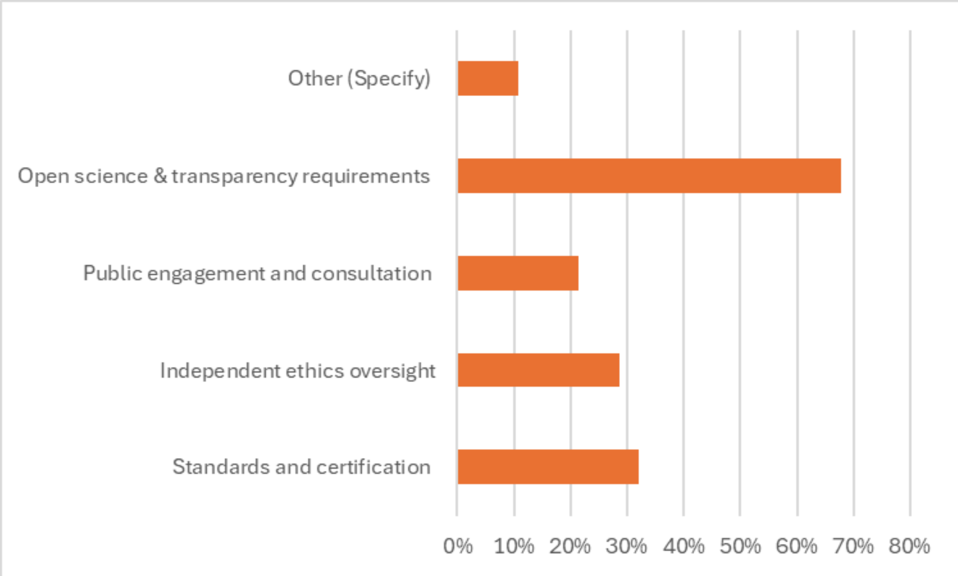

Figure 11 Governance mechanisms for liquid electronics.

The respondents offered a variety of **recommendations** to ensure the ethical deployment of liquid electronics. A central theme was the *importance of clear, accessible, and widespread communication about the technology*, including its potential risks and benefits. Many highlighted the need for *transparency* throughout the development process, especially regarding data, experimental procedures, the disclosure of collaborations, funding sources, and patents. Several responses called for the *standardisation of tests*, independent peer review, and strong involvement from both scientific communities and wider society.

Ensuring *equal access* to raw materials, scientific knowledge, and technological benefits—particularly for developing countries—was frequently mentioned. Some suggested open databases and international rules to promote fairness and avoid oligopolies. Respondents also emphasised the importance of *data sovereignty, safety, reliability, and robust waste management and recycling systems.* There were calls for extra regulatory mechanisms for biohybrid technologies and for regulations to address negative externalities at later stages.

A few respondents noted the need for *ethical education*, such as discussing these topics in schools, and for public awareness of any harmful effects. Others acknowledged the challenge of providing recommendations given the novelty of the field, expressing uncertainty or stating they did not know how to proceed. Overall, the recommendations reflected a desire to advance innovation responsibly, without compromising human values, ecological integrity, or fairness in access and participation.

Looking at next +20 years fields of applications, in agriculture, there is still uncertainty regarding the potential applications of advanced computing technologies, and specific uses are yet to be identified. One promising area is *low-level computation in extreme or harsh conditions, especially where access to energy sources is limited.*

In medicine, significant advancements are anticipated. For instance, it is expected that liquid-based commercial memories could become available within five years, while entirely liquid prototypes for computing may emerge in the next 20 to 35 years. These developments could revolutionise

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healthcare by enabling non-invasive monitoring and supporting the use of wearables, healthcare devices, and robotics in extreme conditions.

Moreover, the trend towards computing on the edge is growing, particularly for monitoring remote or extreme environments. However, energy-intensive computing, such as artificial intelligence, remains a challenge due to its substantial power requirements.

In twenty years, the **most significant opportunities** provided by liquid electronics are seen by many as true game changers, potentially fostering a *more equitable society*. Experts anticipate major advances in medical and agricultural applications, along with the development of advanced remote sensing and analytical capabilities. Others predict that the sector will be revolutionized by new technologies with potential uses in various fields, also improving computing and allowing seamless integration between humans and biological devices. In particular, the emergence of adaptive and self-healing systems is envisioned—systems capable of connecting living and artificial matter—as well as innovative medical implants and therapeutic devices. Modular components, self-repair functionalities, energy and food applications, and the possibility of replacing traditional electronics in low-power scenarios are also expected to play a key role. There is also anticipation for eco-friendly and cost-effective solutions, sensors able to interface naturally with biological or ecological environments, and a significant boost to space research. At the same time, some acknowledge that many possibilities have yet to emerge or be identified, highlighting how the future of liquid electronics is still partly unknown and full of promise.

In 20 years, the **main risks** of liquid electronics may include increased control over individuals, abuse, privacy and data concerns, unregulated military and defense use, biohazards, challenges in packaging and preventing leaks, issues with scalability, compatibility, material stability, and ethical considerations from rapid adoption without reflection. Other potential problems involve unforeseen externalities from autonomous systems, the effects of interfacing with living beings, lack of cost-effectiveness, and insufficient regulation or oversight. Several respondents also emphasized the importance of transparency regarding possible harms and ensuring public bodies regulate the technology.

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7 CONCLUSIONS AND RECOMMENDATIONS

The ethical and social exploration of the COgITOR project has provided a comprehensive view of how **liquid electronics** may evolve from scientific innovation to societal transformation. The findings reveal both opportunities and challenges linked to sustainability, governance, and public trust.

The deliverable underscores that COgITOR's liquid-state technologies—self-healing, fault-tolerant, and energy-efficient—embody a new paradigm of responsible and inclusive innovation. The analysis followed the principles of RRI, focusing on sustainability, safety, responsibility, and fairness as guiding pillars.

From an environmental and ethical standpoint, liquid electronics have the potential to **minimize ecological impact** by replacing rare or toxic raw materials with **recyclable and non-hazardous components** such as $BiFeO_3$ nanoparticles, hydrogels, and soft polymers. The project's commitment to **circular design** and low-energy fabrication methods aligns with the objectives of the EU Green Deal and the UN Sustainable Development Goals. Future work should continue to integrate **LCA** and develop standards for safe recovery and reuse of materials at end-of-life.

In terms of **human health and safety**, COgITOR ensured compliance with REACH standards and implemented strict safety protocols for nanoparticle handling and synthesis. The ethical importance of **responsible sourcing** emerged strongly, stressing transparent supply chains and alignment with OECD guidelines to mitigate risks associated with critical materials like bismuth and iron.

From a **social and economic perspective**, COgITOR technologies will likely reshape the European industrial landscape. They introduce new employment opportunities requiring cross-disciplinary expertise that combines materials science, digital skills, and sustainability awareness. The project's gender-balanced and inclusive structure reflects Europe's vision for a fair digital transition.

Public engagement is identified as a decisive factor for societal acceptance. Surveys show cautious optimism—stakeholders recognize the **potential in robotics, healthcare, and energy harvesting**, yet express concern about dual-use risks and data transparency. Clear communication, open science practices, and transparent governance were consistently highlighted as necessary to build long-term public trust.

Regulatory frameworks, however, remain fragmented. There are no harmonized **standards or CE conformity procedures** for hybrid, adaptive, or fluidic systems. To address this gap, the report recommends that European agencies (ECHA, CENELEC, ISO) collaborate on new definitions and guidelines, possibly through the creation of a **"Liquid Technologies Observatory"** to monitor safety, ethical compliance, and market readiness.

Stakeholder consultations further confirmed the value of transparent communication, equitable access to innovation, and clear regulation. Respondents emphasized open data, standardized testing, and ethical education as priorities to ensure a fair and sustainable rollout of liquid electronics.

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Key Takeaways and raccomandations:

- Sustainability, safety, responsibility, and fairness are the core ethical pillars guiding COgITOR.
- Circular design and recyclable, non-toxic materials can drastically reduce environmental impact.
- Responsible sourcing and transparent supply chains are essential for material ethics.
- Workforce transformation will require new interdisciplinary skills and gender-inclusive policies.
- Public trust depends on transparency, open science, and ethical governance.
- Regulatory innovation is needed to classify, certify, and standardize liquid-state devices.
- Liquid electronics have strong long-term potential in healthcare, robotics, and sustainable energy applications.

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8 ANNEXES

Annex I – Survey

☑ Save a backup on your local computer (disable if you are using a public/shared computer)

Stakeholder Consultation Survey
Long-term Ethical & Social Implications of Liquid Electronics

Fields marked with * are mandatory.

Disclaimer
The European Commission is not responsible for the content of questionnaires created using the EUSurvey service - it remains the sole responsibility of the form creator and manager. The use of EUSurvey service does not imply a recommendation or endorsement, by the European Commission, of the views expressed within them.

Intro

A new COlloidal cybernetIc sysTem tOwaRds 2030

COgITOR is a project funded under the topic H2020-FETOPEN-2018-2020 / H2020-FETOPEN-2018-2019-2020-01 programme, aiming at developing a liquid state cybernetic system prototype. Holonomic memory and computing, pressure sensing, and energy harvesting from thermal gradients will be achieved using colloids. The prototype will be tested in extreme environments for different potential applications.

For further information, please refer to COgITOR website: https://www.cogitor-project.eu/

* This survey is related to the Long-term Ethical & Social Implications of Liquid Electronics within the European initiative COgITOR.

If you want to proceed with the survey, please accept the disclaimer: I acknowledge that the answers that I will provide in this survey will be used to gather information in the COgITOR project. I agree with the Privacy Policy available at this link: https://www.cogitor-project.eu/privacy-policy/

- ◯ Yes
- ◯ No

Submit

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Participant Profile

Name / Affiliation / Role (optional)

* Type of organisation:

- ◯ University / RTO
- ◯ SME / Industry
- ◯ Policy / Regulatory body
- ◯ NGO / Civil society
- ◯ Other (specify)

* Field of expertise

- ◯ materials
- ◯ computing
- ◯ energy
- ◯ robotics
- ◯ ethics
- ◯ policy
- ◯ social sciences and humanities
- ◯ other (specify)

* Previous experience with liquid-state or unconventional electronics?

- ◯ Yes
- ◯ No

Awareness & Perception

On a scale of 1 –5, how familiar are you with the concept of liquid electronics?

Move the slider or accept the initial position.

Very unlikely — Very likely

3

1 — 5

On a scale of 1 –5, what is your initial perception of the societal potential of liquid electronics?

Move the slider or accept the initial position.

Very negative — Very positive

3

1 — 5

* Which application do you consider the most relevant for liquid electronics?

- ◯ Healthcare & implants
- ◯ Wearables & consumer electronics
- ◯ Robotics & automation
- ◯ Energy harvesting & storage
- ◯ Extreme environment exploration
- ◯ Other (please specify)

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Ethical Concern

Please rate your level of concern on the following aspects related to liquid electronics (Likert scale 1min – 5max):

	1	2	3	4	5
* Environmental sustainability (materials, recyclability, waste)	○	○	○	○	○
* Human health and safety	○	○	○	○	○
* Data privacy and human–machine interaction (e.g., implants, wearables)	○	○	○	○	○
* Equity and accessibility (who benefits, who is excluded)	○	○	○	○	○
* Dual-use risks and misuse (e.g., surveillance, military)	○	○	○	○	○

Which ethical concern do you see as most urgent to address in the next 10 years related to liquid robotics?

Social Implications

* What positive social impacts could emerge from large-scale use of liquid electronics?

* Do you foresee any risks or unintended consequences as well

* In your view, what factors will most influence public acceptance of liquid electronics?

- ☐ Transparency of risks/benefits
- ☐ Clear regulation & standards
- ☐ Demonstrated safety in healthcare/consumer use
- ☐ Sustainability credentials
- ☐ Media / public communication
- ☐ Other (specify)

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Governance & Recommendations

How adequate are current regulatory frameworks for dealing with such technologies?
Move the slider or accept the initial position.

Not adequate at all — Very adequate

3

1 — 5

* What type of governance mechanisms should be prioritized in liquid electronics?

- ☐ Standards and certification
- ☐ Independent ethics oversight
- ☐ Public engagement and consultation
- ☐ Open science & transparency requirements
- ☐ Other (Specify)

* What recommendations would you propose to ensure ethical deployment of liquid electronics?

Forward-looking Vision

* In 20 years, what do you expect will be the dominant application field of liquid electronics?

* In 20 years, what do you expect will be the single greatest opportunity of liquid electronics?

* In 20 years, what do you expect will be the single greatest risk of liquid electronics?

Closing

* Would you like to stay informed about the outcomes of the COgITOR ethics and social impact deliverable?

- ○ Yes
- ○ No

Submit

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